

THE MEASUREMENT AND SPECIFICATION
OF COLOR

863

By B. A. BRICE

Eastern Utilization Research Branch
United States Department of Agriculture

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Color is a factor of quality in many agricultural and food products; for example, raw wool, cotton, silk, rosin, maple sirup, honey, sucrose sirups, refiners' sirups, molasses, spices, flour, starch, sugar, vegetable oils, raw and processed fruits and vegetables. Many of these products are graded and priced according to color. Change of color in the processing or storing of fruits and vegetables is evidence of chemical change and is usually accompanied by flavor change. In order to retain high quality and palatability, the changes in color, flavor, and texture in processing must usually be held at a minimum, and a great deal of research is necessary to accomplish this.

The measurement and specification of color is "color science," combining segments of physics, chemistry, physiology, and psychology for its complete understanding. A great deal of progress has been made, particularly in the last 20 years, in the methods of measuring and specifying color and in the systematic naming of colors. With modern photoelectric instruments, and psychophysical data adopted

by international agreement, the measurement and specification of color can be quite straightforward.

One of the general definitions of color is as follows: Color is the general name for all sensations arising from the activity of the retina of the human eye and its attached nervous mechanism when light strikes the retina; light being radiant energy approximately 0.4 to 0.8 micron in wave length. With this definition in mind it is clear that it is not proper to speak of the color of an object. Color is in the mind and is not, strictly speaking, a property of the object. The color perceived when the eye views an illuminated object depends on three things: the spectral composition of the light source, the chemical and physical character of the object or colorant, and the spectral sensitivity characteristics of the eye viewing the object. If any one of these three factors is changed, the color perceived will change.

In order to talk intelligently about the color of an illuminated object, we must agree upon a standard light source and a standard observer. Then the problem of color measurement and color specification will reduce to measuring the light-reflecting or light-transmitting properties of the object, followed by appropriate calculations. Such standards have been adopted by the International Commission on Illumination (C.I.E.). Figure 1 illustrates the spectral distribution of energy for C.I.E. standard light sources A and C. Illuminant A is an incandescent light operated at 2854°K. Illuminant C is the same light modified by two filters of specified composition, and approximates average daylight in color. This is the most commonly used standard illuminant. Also shown in Figure 1 is the luminosity curve of the C.I.E. standard observer based on spectral response data for a number of normal observers referred to an equal-energy spectrum.

Color has three recognizable attributes: hue, saturation, and lightness. *Hue* is the attribute associated with the sensation of redness, yellowness, blueness, etc. *Saturation* is the attribute associated with strength of hue or freedom from admixture with white. *Lightness* is associated with the brightness aspect of a color and usually depends on the relative luminous flux transmitted or reflected by the colorant. The combination of hue and saturation can be described by the term chromaticity. Black, white, and gray are achromatic colors; they differ only in lightness. Under ideal observing conditions, the eye can distinguish between about seven million reflected colors differing perceptibly in combinations of hue, saturation, and lightness. If we could find numbers to represent the hue, saturation, and lightness of a color when viewed under a standard light source by a standard observer, we would have an extremely useful system of color specification. This can be done by means of the C.I.E. coordinate system.

Color measurement is based on the experimental fact that most colors can be matched by combining three primary lights, red, green, and blue. The relative amounts of three selected primaries required to match a given color are called *tristimulus values* of the color. The

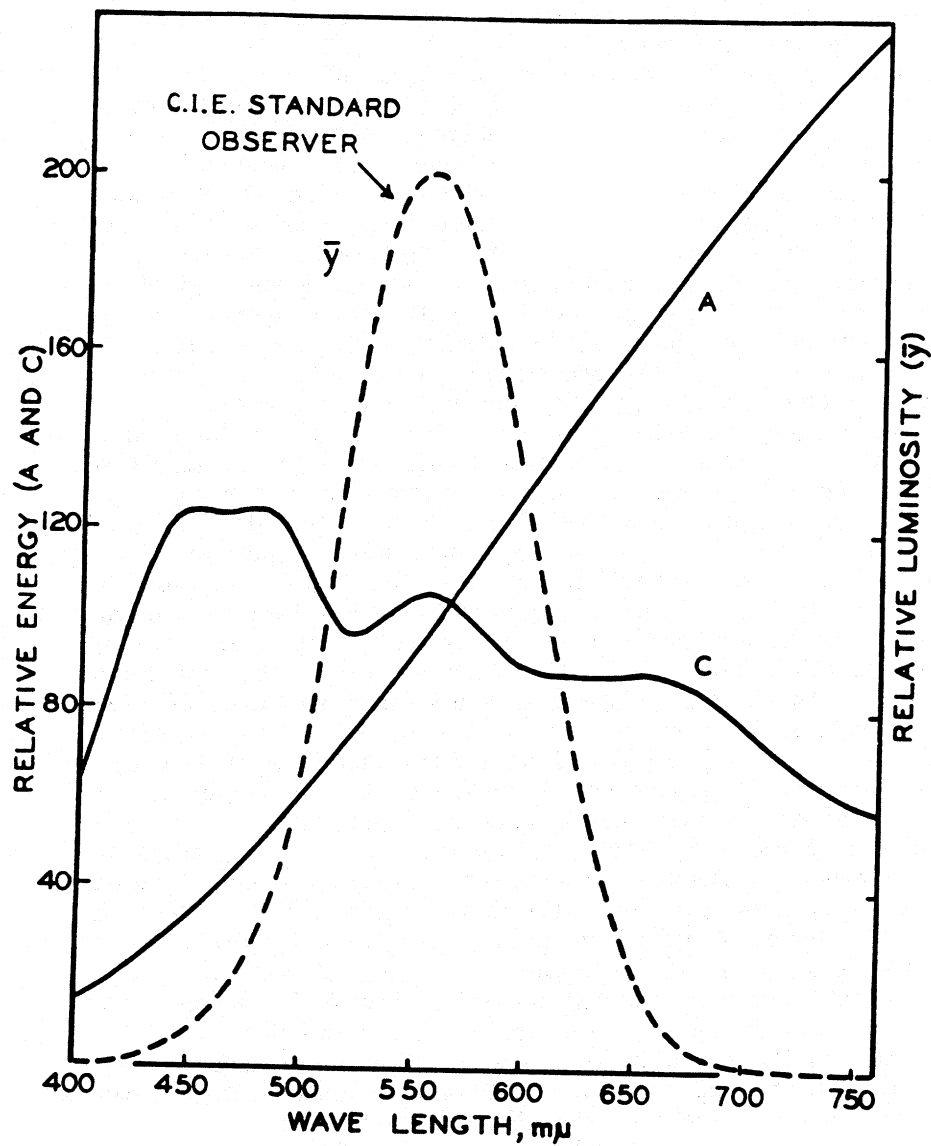


FIGURE 1.
Relative distribution of radiant energy in the visible spectrum for C.I.E. Illuminants A and C. Relative luminosity function (\bar{y}) for the C.I.E. standard observer.

C.I.E. primaries are imaginary, since real primaries cannot be found which can be combined to match the highly saturated hues of the spectrum. The characteristics of these primaries and the C.I.E. standard observer are embodied in tabulated data for the tristimulus values of spectrum stimuli, \bar{x} , \bar{y} , and \bar{z} , expressing the relative amounts of

the primaries required to match the hues of various wave lengths of the equal-energy spectrum. These data are based on extensive measurements with real primaries. The values of \bar{y} were chosen to correspond exactly with the luminosity curve of the standard observer (Figure 1). The red, green, and blue *chromaticity coordinates* of the spectrum colors are calculated at each wave length by $x = \bar{x}/(\bar{x} + \bar{y} + \bar{z})$, $y = \bar{y}/(\bar{x} + \bar{y} + \bar{z})$, and $z = 1 - (x + y)$. A plot of x vs. y gives the C.I.E. chromaticity diagram in the x, y plane, which is shown in Figure 2. The locus of the chromaticity coordinates of the spectrum forms the boundary of all realizable colors or chromaticities. Every conceivable chromaticity can be represented by a point within this

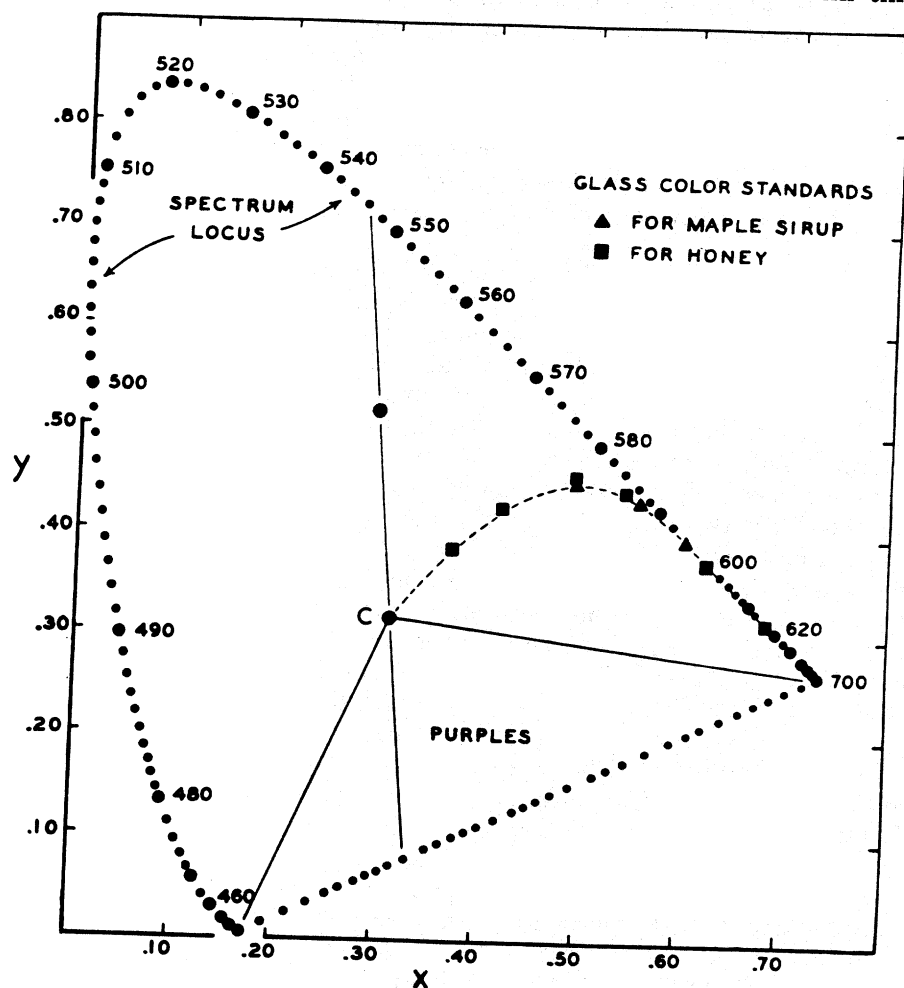


FIGURE 2.
C.I.E. chromaticity diagram.

locus and the line connecting its ends, and every point within these boundaries represents a chromaticity which can be made by a mixture of the three imaginary primaries. The red primary is located at $x=1, y=0$; the green primary at $x=0, y=1$; and the blue primary at $x=0, y=0$. The point at C is the "white point" representing the chromaticity coordinates of Illuminant C.

The tristimulus values of a transparent sample viewed under Illuminant C are obtained by integrating composite curves formed by products $x_\lambda E_\lambda T_\lambda$, $y_\lambda E_\lambda T_\lambda$, and $z_\lambda E_\lambda T_\lambda$, usually at $10 \text{ m}\mu$ wave length intervals, where x_λ , y_λ , and z_λ are the tristimulus values of the spectrum, E_λ is the spectral distribution of energy in Illuminant C (Figure 1), and T_λ the spectral transmittance of the sample. Several methods of integration are available. The integrated tristimulus values are X, Y, and Z; and the chromaticity coordinates of the sample are $x=X/(X+Y+Z)$, $y=Y/(X+Y+Z)$, and $z=1-(x+y)$. The luminous transmittance, in per cent, is simply $Y/1000$, and represents a numerical specification for the lightness attribute of the color. If the sample is opaque, spectral reflectance values R_λ are required for calculating the chromaticity coordinates, and per cent luminous reflectance is $Y/1000$.

The dotted line in the mixture diagram of Figure 2 is the locus of chromaticity coordinates of solutions of caramel in glycerin in 31.5-mm. depths. Samples of selected solutions are close spectral matches and color matches with samples of maple sirup and honey in the same depth. The chromaticity coordinates of maple sirup and honey samples follow the same locus and are essentially non-metameric. The system represents a one-dimensional color system as far as chromaticity is concerned. The three triangular points on this curve represent the chromaticity coordinates of the new U. S. Department of Agriculture glass color standards for maple sirup, designated by the names Light Amber, Medium Amber, and Dark Amber. The six square points represent the coordinates of the Department's new glass color standards for extracted honey, designated Water White, Extra White, White, Extra Light Amber, Light Amber, and Amber. Spectral transmission curves for the glass standards are different in shape from the curves of caramel-glycerin solutions of equal color under Illuminant C. The pairs are, therefore, slightly metameric. The C.I.E. system of color measurement aided in the selection of suitable amber glasses for these standards and also furnished a vastly improved description or set of specifications for their colors. For example, the specifications for the Light Amber glass standard for maple sirup are $x=0.486$, $y=0.447$, and $T=38.9\%$. The coordinates x, y constitute a basic numerical specification for chromaticity, and the luminous transmittance T for lightness. These figures mean that the chromaticity of the Light Amber standard, as seen by the C.I.E. standard observer under standard Illuminant C,

is equal to that of a mixture of 48.6% of the red primary, 44.7% of the green primary, and 6.7% of the blue primary; and that the glass standard transmits 38.9% of the incident light. Before these glass standards were developed, the color standards for maple sirup were caramel-glycerin solutions specified only by transmittance of a 1-cm. depth at wave length 560 $m\mu$. Such a specification is inadequate since preparations from different caramel sources are slightly metameric, i.e., two preparations having equal transmittances at 560 $m\mu$ may have noticeably different colors under Illuminant C. The previous color standards for honey were described in terms of certain scale readings on a standard Pfund Honey Grader, a visual comparator equipped with an undescribed amber glass wedge. The new glass standards are more convenient for inspection and grading purposes, and the C.I.E. specifications constitute a more satisfactory description of their colors.

Separate numerical specifications for the hue and saturation attributes of a color can readily be derived from the chromaticity diagram in terms of *dominant wave length* and *excitation purity*. A straight line in the chromaticity diagram represents a series of chromaticities which can be produced by mixing lights having chromaticity coordinates at the ends of the line. For example, the line drawn from the white point C to intersect the spectrum locus at 546 $m\mu$ represents a series of green stimuli all resembling spectrum wave length 546 $m\mu$ in hue, but increasing in saturation as the spectrum locus is approached. The coordinates of a green colorant are represented by the circular point about midway on this line. The wave length 546 $m\mu$ is the dominant wave length of any point on this line and, therefore, yields a numerical specification for the hue attribute of this colorant. The excitation purity is simply the ratio of the distance between the white point and the colorant point to the distance between the white point and the spectrum locus, about 50% in this case. This furnishes a numerical specification for the saturation attribute. For the Light Amber maple standard, complete specifications in this form, for hue, saturation, and lightness are: dominant wave length 581.7 $m\mu$, excitation purity 82.0%, and luminous transmittance 38.9%.

The combination of a spectrophotometer and this C.I.E. coordinate system is applicable to a wide variety of problems and is widely used in industry for both research and control purposes. The combination provides a unique and fundamental system of color specification; also it provides a detailed picture of the color system being studied that no other system can approach. However, it has the disadvantages that it requires expensive equipment and is usually time-consuming in its application.

Short cuts, simpler instruments, and simpler procedures are available which are satisfactory for many color problems. Outstanding among these are photoelectric tristimulus colorimeters such as the

Hunter Color-Difference Meters, the Colormaster Differential Colorimeter, and the Color Eye. Such instruments are equipped with three filters so chosen that the spectral distributions of the filter-lamp-photocell combinations conform as closely as possible to the spectral distributions of the C.I.E. tristimulus functions applied to Illuminant C. Three determinations of reflectance or transmittance of a specimen are required for an evaluation of color, one for each color filter. The limitations of these instruments arise principally from the fact that color filters cannot be found which duplicate perfectly the desired tristimulus functions. The result is that true x and y chromaticity coordinates can be obtained only for near-whites. The x,y chromaticity diagram corresponding to an instrument of this type is distorted except near the white point. The farther we are from the white point the greater the error in determining true x and y coordinates. However, such instruments may measure accurately the difference in x,y coordinates between a standard and a sample, if this difference is not too large and if the standard and sample are not highly metameric (i.e., if they do not differ widely in spectral reflection or transmission). In spite of their limitations these instruments are rapid and can yield very useful indexes for hue, saturation, and lightness.

Other short cuts can be made by use of transmittance or reflectance measurements at one or more wave length positions with a spectrophotometer or an abridged spectrophotometer. In this way we can often get a number or set of numbers which *correlate* with color or color change but, strictly speaking, do not *measure* color. For example, in following the change of color in the heat processing of maple sirup we have used absorptivity at $450\text{ m}\mu$ as a rapid index of color. This "color index" is absorbance per cm. referred to standard sirup density of 86.3 g. of solids (as sucrose) per 100 ml. It is imperfect, however, since two sirups may have the same absorptivity or "color index" but have noticeably different colors. Another example, attended by difficulties, is the attempt of the American Oil Chemists' Society to find a rapid index of color for vegetable oils in terms of transmittance measurements at several wave lengths with a spectrophotometer. Unfortunately, the oil colors are often highly metameric and the instrument chosen is a wide-band spectrophotometer. Numbers obtained on different instruments for a given sample do not always agree precisely, and difficulty has been experienced in finding a set of numbers which correlate satisfactorily with the previously used Lovibond glass combinations. Such rapid methods are most successful when applied to one-dimensional color systems, i.e., when the colorants involved closely follow a line on the chromaticity diagram. The evaluation of color in capsicum spice extracts by Moster and Prater is a good example. They used essentially a two-wave-length transmittance method with a Beckman spectrophotometer, and obtained highly satis-

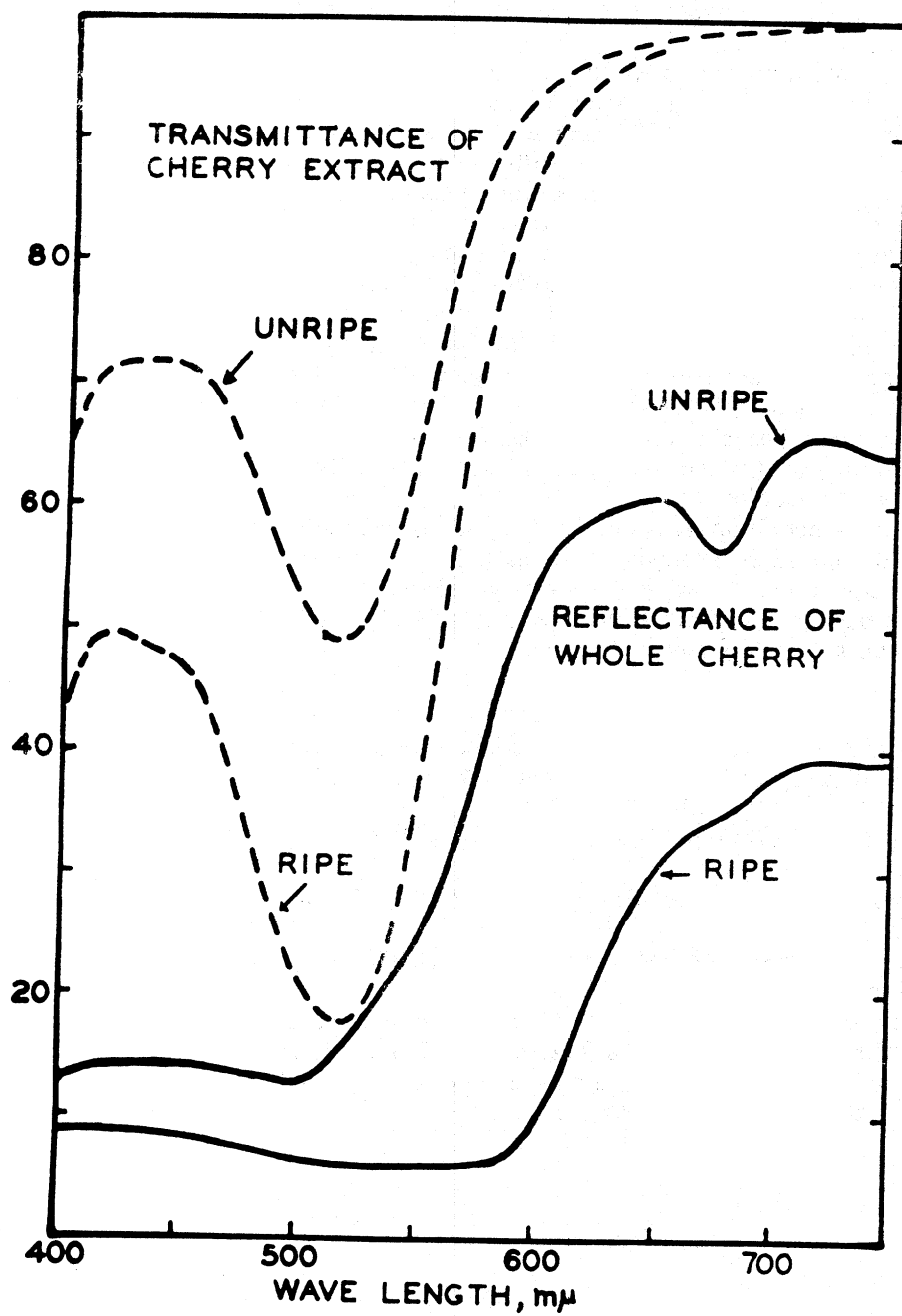


FIGURE 3.
Spectral reflectance curves (—) for ripe and unripe whole cherries. Spectral transmittance curves (---) for filtered water extracts of cooked cherries, ripe and unripe.

factory correlation with the x chromaticity coordinate and with Lovibond numbers.

Another example is an attempt to rapidly evaluate the color of canned sour cherries during processing studies. Figure 3 shows spectral reflectance curves for whole fresh cherries, ripe and unripe. Differences in the curves are due primarily to differences in anthocyanin and chlorophyll pigment contents. Reflectance measurements at one wave length, or a function of reflectance at two wave lengths, on the fruit and drained juice homogenized in a blender, offer a means of rapidly evaluating color. However, since the anthocyanin pigment is readily extractable with water or alcohol, a transmittance or absorbance measurement at one wave length on the filtered extract was considered more satisfactory. The dotted curves of Figure 3 illustrate spectral transmittance curves for filtered extracts of typical ripe and unripe cooked sour cherries. Absorbance at 520 $m\mu$, the wave length of the absorption maximum, has proved to be a reasonably satisfactory index of color in processing studies.

Abridged methods have been applied to many other food products. It should be recognized that such methods often have severe limitations; and that, strictly speaking, in such cases we are *evaluating color in terms of* transmittance or reflectance measurements at specified wave lengths rather than *measuring color*.

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